Stratigraphy and Water Levels in the Arapahoe Aquifer, Douglas County Area, Denver Basin, Colorado[1]

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1. Manuscript received June 24, 2004; Accepted July 24, 2004
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"With the tremendous expansion of suburban population after WWII, several hundred wells have been drilled into the Arapahoe Formation in suburban areas ...the result has been a rapid decline in head.....amounting locally to more than 160 feet. The situation has become so serious that the Veterans Administration and the Federal Housing Administration will no longer approve loans for housing developments that are dependant on deep wells for their principal source of water supply" (McLaughlin, 1955, p. 63).

"In the areas which have experienced excessive annual water level declines, local and state planning directors should discourage the construction of new developments which must rely totally on bedrock water resources" (Romero, 1976, p. 86).

ABSTRACT

Analysis of the stratigraphic character of the bedrock Arapahoe aquifer in the Douglas County area indicates that the aquifer accumulated as a fluvial distributary fan deposited as the Rocky Mountains rose west of the fault-bounded and westward-thickening Denver Basin. By placing the aquifer in this genetic context, useful interpretations and analyses of its water-producing potential are possible. The potentiometric surface in this critical aquifer is falling at about 30 ft/yr, and the aquifer will transition from confined to unconfined conditions over the next couple of decades. Water resource planners must anticipate that existing water wells will suffer production declines when this transition occurs. Alternate sources of potable water must be developed, as drilling additional wells into the aquifer provides only a short-term solution.

INTRODUCTION

Bedrock aquifers occur within the synorogenic fluvial and near-shore marine sediments that accumulated in the Denver Basin at the onset and during the Laramide Orogeny. The retreat of the Western Interior Seaway was followed, in the latest Cretaceous and early Tertiary, by river systems flowing from the Front Range. These rivers filled the proximal (mountain-side) portions of the Basin with coarse-grained strata more favorable for water retention than the fine-grained strata of the distal (high plains-side) of the Basin. Changes in the outflow location of river systems sourced from the mountains also influenced the spatial distribution of porous and permeable rock facies. The *depositional environment* exerted a primary stratigraphic control on aquifer quality. Equally important is the *subsequent erosion* that removed much of the synorogenic strata with aquifer potential thus further limiting the amount of available water. The outcrops and subsurface distribution patterns of the aquifers of the Denver Basin are truncated on the north by the South Platte River and on the south by the Arkansas River. The thickest remaining accumulation of these strata occurs in the vicinity of the drainage divide between the two river systems, an area known as the Palmer Divide (Fig. 1).

The Denver Basin is broadly asymmetric with a depositional axis located approximately 30 km from the mountain front. Regional cross sections (Fig. 2) illustrate the general configuration of the Basin. The distribution and diversity of facies patterns reflect ancient depositional environments. In general, the Fox Hills Sandstone occurs as a series of offlapping shingles associated with the episodic northeastward retreat of the Western Interior Seaway; the Laramie Formation contains coal beds and fluvial channel sandstone beds, particularly on the western side of the Basin; and the overlying Arapahoe, Dawson, and Denver formations are composed of alluvial materials derived under varying conditions from rivers draining the uplifted Front Range of the Rocky Mountains (Fig. 3).

The bedrock aquifers in the Denver Basin are given the same names as those used in traditional geological formation mapping, although hydrologists and field geologists have different rock volumes in mind (Fig. 4). For example, the Laramie/Fox Hills aquifer is composed of the lower portion of the Laramie Formation (if it contains sandstone beds) and the bulk of the Fox Hills Sandstone; the Arapahoe aquifer is composed of what has been termed the Arapahoe Formation (Emmons et al., 1896) as well as a portion of the overlying Dawson Arkose or Denver Formation in the Denver area. In the terminology of Raynolds (2002) the Arapahoe aquifer is within the lower portion of the D1 sequence. The Denver and Dawson aquifers are

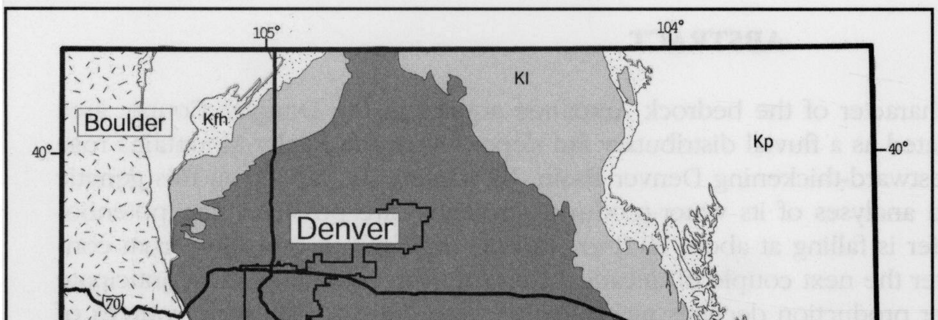

Figure 1. Index map showing the study area (enlarged as Figure 8) and cross section location (Figure 10) on the western side of the Denver Basin.

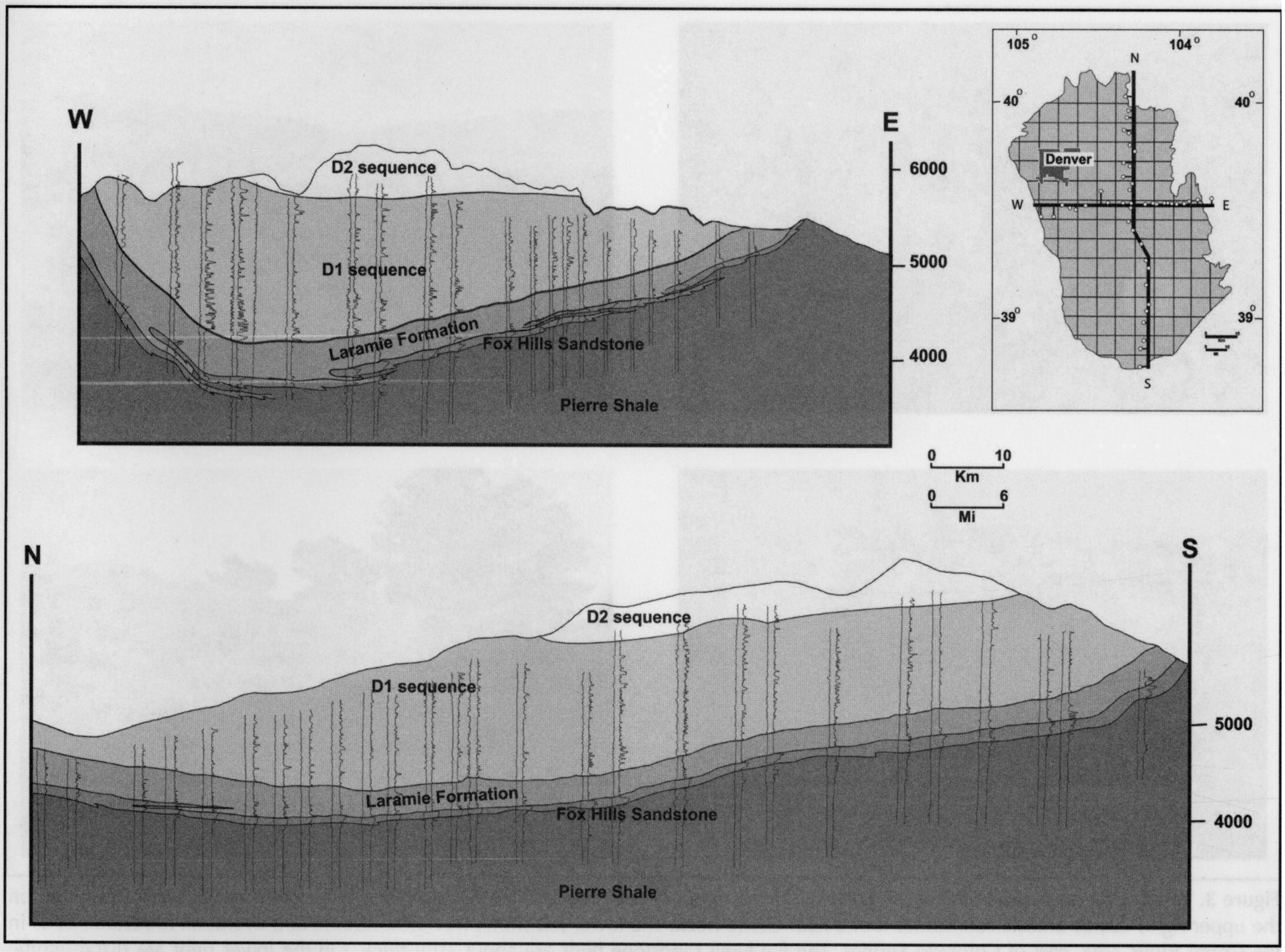

Figure 2. Regional north-south and east-west oriented cross sections across the Denver Basin. Modern erosion has removed strata from the periphery of the study area. Electric logs are from oil and gas test wells.

only loosely congruent with the rock units of the same names. The Denver Formation is an andesitic facies of synorogenic sediment that interfingers with an arkosic facies termed the Dawson Arkose (e.g., Scott, 1962; Mayberry and Lindvall, 1972, 1977). Certain areas of the Denver Basin may show no mapped Denver Formation although the aquifer of that name is continuously mapped across the region (e.g., Robson, 1989; Topper et al., 2003). Geologic maps of the area use broader facies groupings to establish regional mapping units (Trimble and Machette, 1979). More detailed geologic mapping in the Basin can result in the definition of facies packages (see Mayberry and Lindvall, 1972, 1977; Thorson, 2003, 2004; Thorson and Madole, 2002; Morgan et al., 2004). In summary, defined aquifer boundaries are not tied directly to facies boundaries although they may locally coincide with them.

GEOLOGIC BACKGROUND

The stratigraphy of the Denver Basin has been the subject of research for over a hundred years; historical summaries are presented in Crifasi (1992), and Raynolds (2002). Stratigraphic work by Raynolds (1996, 1997, 2002) has defined the general internal architecture of the water-saturated sedimentary rocks making up the bedrock aquifers. The current mapping program by the Colorado Geologic Survey has refined and delimited surface facies distribution patterns.

In the synorogenic strata filling the Denver Basin, the bedrock aquifers are composed of layers of sandstone deposited by river systems flowing from the growing Rocky Mountains alternating with the less porous and less permeable mudstone layers accumulated as overbank

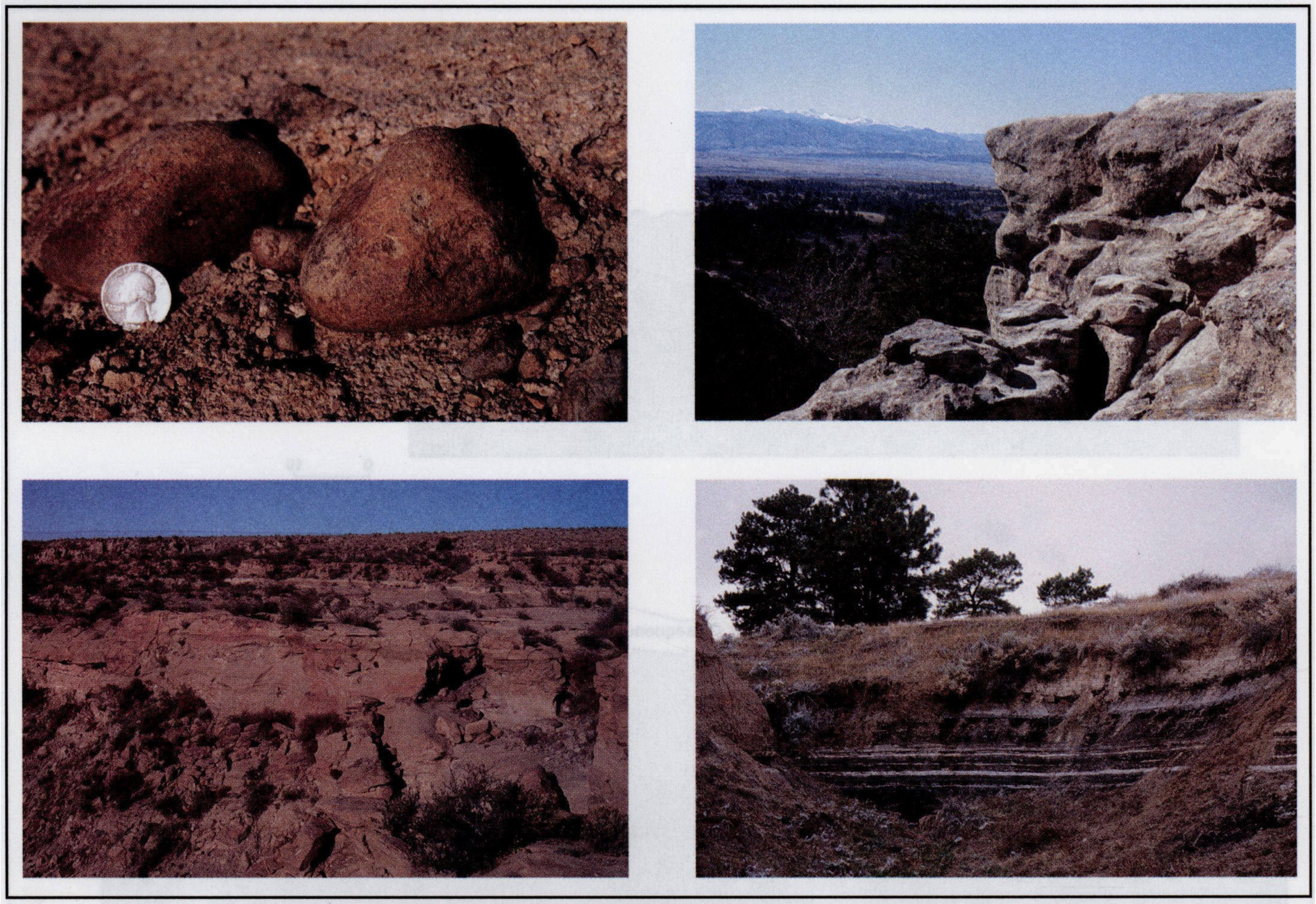

Figure 3. Variable facies found in the D1 sequence. On the upper left are coarse andesitic conglomerates found near Green Mountain, on the upper right, coarse arkosic sandstones found near Castle Rock. The lower left shows fluvial sandstone and overbank mudstone beds in the Corral Bluffs area, east of Colorado Springs. The flat-lying sandstone beds are about 10 ft thick. On the lower right are distal lignitic beds with white kaolinitic volcanic ash beds found east of Kiowa in the Bijou Creek drainage.

deposits (Kirkham and Ladwig 1980). Water occurs in the pore spaces between mineral grains. The proportional size and abundance (porosity) and interconnectedness (permeability) of the pore spaces together with the size and shape of the sandstone layers control the water-yield of the aquifers. Higher water-yield is provided by the more porous and permeable rock in large and interconnected sandstone beds than by the less porous and less permeable rock occurring in thin and discontinuous sandstone beds. Understanding the nature of the bedrock geology and the distribution pattern of sandstone layers can aid in the prediction of water well performance.

The bedrock aquifers in the Denver Basin occur above the marine Pierre Shale that is over 8000 ft thick. This low-permeability, non-aquifer shale comprises the economic base, or lower limit, to the bedrock aquifer system. The bedrock aquifers span a set of geological formations that start with the shoreline sandstones associated with the retreat of the Western Interior Seaway. As illustrated in Figure 5, these aquifers are found in rocks that represent, from the bottom up: the retreat of the seaway, coastal plain conditions, and overlying sandstone rock units deposited by rivers.

CURRENT DATABASE AND METHODOLOGY

The integration of surface and subsurface data allows for synthesis of the geological history responsible for the accumulation of the bedrock aquifers. Oil and gas exploration wells penetrate the entire aquifer succession, as their targeted hydrocarbon reservoirs occur sealed beneath the Pierre Shale. Electric logs from these wells, together with logs from water wells, are combined with surface geological studies to comprise the database used for this report. The oil and gas well electric logs are available through the

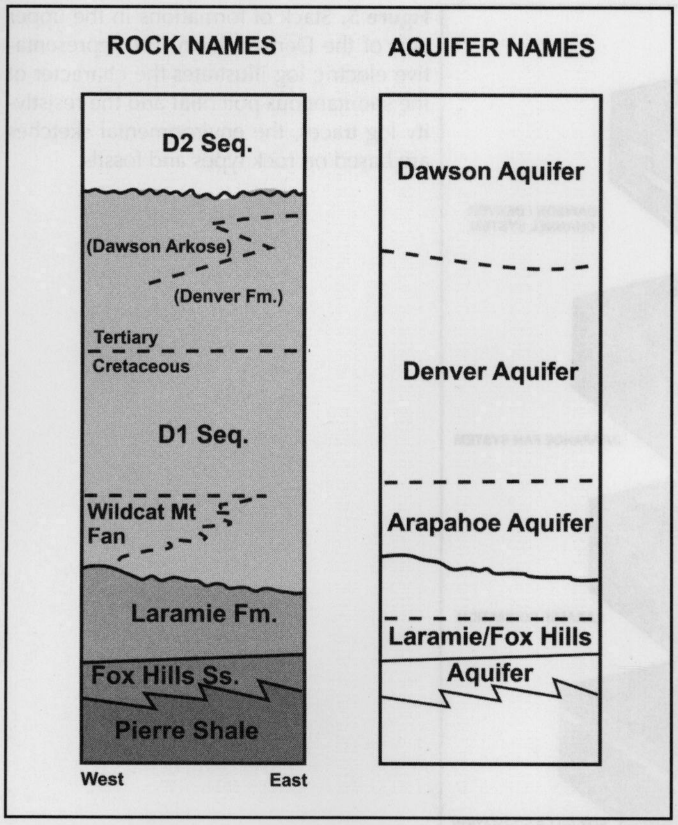

Figure 4. Nomenclature chart illustrating rock and aquifer names in the Denver Basin. Dashed lines represent transitional boundaries, wavy lines are unconformities. The base of the Fox Hills Sandstone interfingers with the Pierre Shale. As discussed in the text, there is not a direct correspondence between geological units and aquifers.

Colorado Oil and Gas Conservation Commission; the water well electric logs from the Colorado Division of Water Resources.

Examination of well cuttings and cores from the Arapahoe aquifer confirms that high resistivity electric log signatures are characteristic of porous and permeable sandstone beds. Gamma ray and spontaneous potential logs also indicate sandstone facies; their traces corroborate the resistivity curves. Figure 6 illustrates the lithology pattern from a core obtained near Castle Pines, in Douglas County. SEM photomicrographs from the Arapahoe aquifer interval in this core are illustrated in Figure 7. To make the maps for this study, interpretations of sandstone vs. mudstone were made from electric logs. Over 140 wells were examined within an area in excess of 1000 mi^2. Cut-off points about one third of the way between the mudstone base line and the maximum resistivity deflection were selected. Deflections greater than the cutoff line were counted and summed as sandstone. While individual sandstone thickness measurements made in this fashion are subjective, the pattern of sandstone thickness distribution is not. Different workers using varying criteria will consistently arrive at similar mapped thickness patterns.

THE ARAPAHOE AQUIFER

The Arapahoe aquifer is the most important source of groundwater for the rapidly urbanizing area south and east of Denver. Most residents of Douglas, western Arapahoe, and western Elbert counties rely on this aquifer for their domestic water supplies. Large-diameter municipal wells can yield over 700 gallons of water per minute from this aquifer.

Recharge of bedrock aquifers in the Denver Basin may occur from surface rainfall, mountain-derived streams, and flow between aquifer units. This recharge may be significant for the uppermost layers of the near-surface aquifers. The Arapahoe aquifer, however, receives little or no recharge from surface water and likely receives little recharge from overlying aquifers because of the extremely low permeability of the intervening shale units (Barkmann, this volume). From a practical standpoint, users of this aquifer are mining non-renewable groundwater.

The Arapahoe aquifer contains rocks described as the Arapahoe Formation and the Arapahoe conglomerate together with varying thicknesses of overlying strata that may in places may be mapped as the Denver or Dawson formations (compare Scott's Kassler Quadrangle (Scott, 1963) to Robson et al.'s 1988 map). The usage of the terms Arapahoe conglomerate/Formation has varied through time but generally refers to the lower few hundreds or tens of feet of strata unconformably overlying the Laramie Formation. The Arapahoe aquifer as defined by the State Engineer's Office (e.g., VanSlyke et al., 1988; Topper et al., 2003) is a basin-wide interval of alternating conglomerate, sandstone, and shale that is generally 500-700 ft thick. In the study area, the Arapahoe aquifer is largely coincident with a mappable lobe of sandstone that occurs at the base of the synorogenic strata in the lower part of an unconformity-bounded sequence of rock termed the D1 sequence by Raynolds (1997, 2002, see Fig. 2).

The Arapahoe aquifer has been discussed at considerable length from a hydrologic perspective. Romero (1976) compiled a comprehensive study of the geologic framework and described the characteristics of each bedrock aquifer in the Denver Basin. His set of 1:500,000 scale maps of geologic outcrops and aquifer configurations formed the basis for further studies.

Hillier et al. (1978), compiled an early data set at 1:100,000 scale showing aquifer conditions in the Arapahoe aquifer. Robson et al. (1981) produced a set of 1:500,000 scale maps of the Arapahoe aquifer and described its facies heterogeneity. They note that the aquifer boundaries and those of the Arapahoe Formation

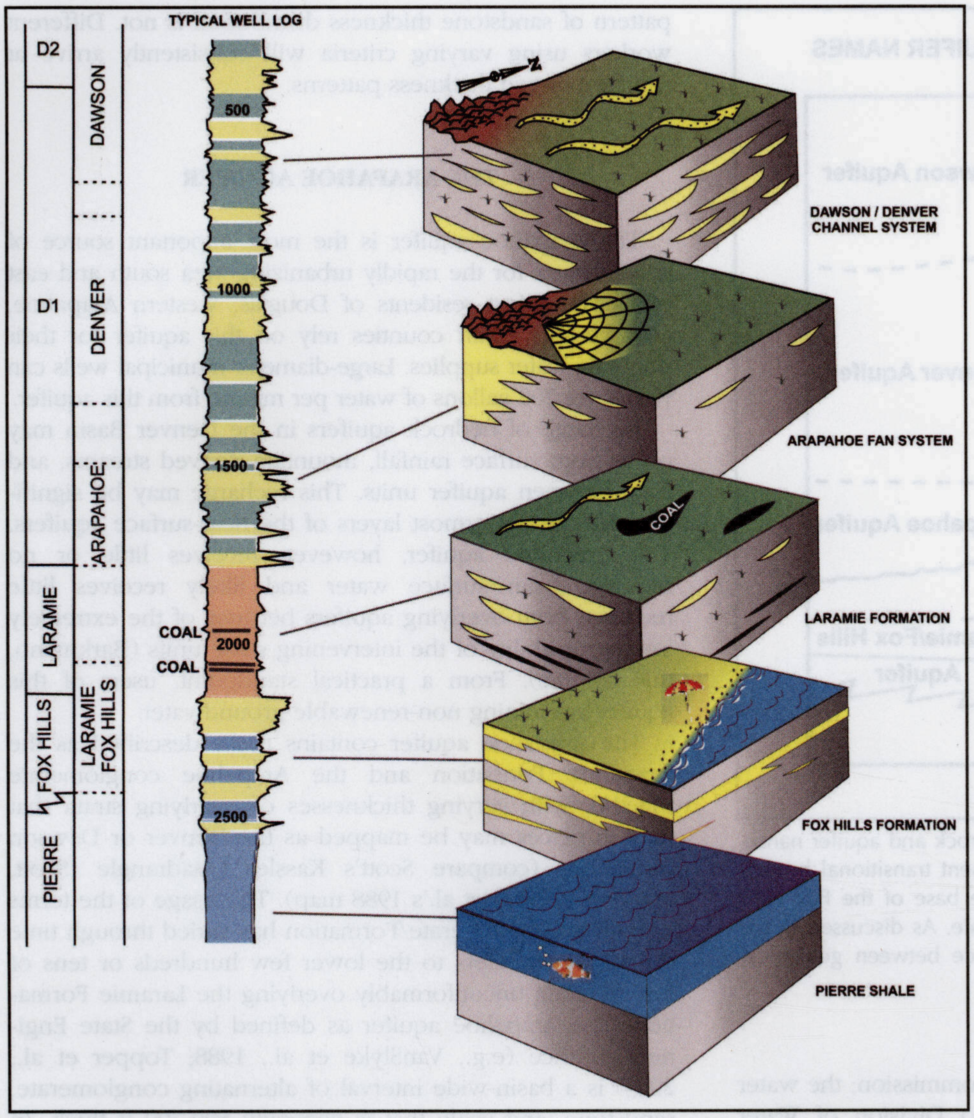

Figure 5. Stack of formations in the upper part of the Denver Basin. The representative electric log illustrates the character of the spontaneous potential and the resistivity log traces, the environmental sketches are based on rock types and fossils.

are not the same, describe the water chemistry, and provide a schematic illustration of the sandstone distribution patterns in the aquifer (their figure 6). VanSlyke et al. (1988) present a 1:200,000 scale map depicting the Arapahoe aquifer interval as having widely variable sandstone content, and note that lateral facies changes strongly control the quality of the aquifer. Like Robson et al. (1981), they provide a sandstone isopach map (their Plate 4). Both isopach maps, lacking a geological model and based on sparse data, are schematic in nature.

Robson (1987, p. 18) discusses the volume of groundwater available in the Denver Basin. By projecting relatively high values for specific yield and transmissivity across the Basin, he arrived at the optimistic value of 269 million acre feet of recoverable water. Robson (1989, p. 28) produced a popular version of his 1987 report in which he notes that the bedrock aquifers of the Denver Basin contain 470 million acre feet of water in storage (stated to be 20% more water than in Lake Erie) and that, in 1985, only 36,000 acre ft/yr were being pumped from the bedrock aquifers. The impression given was one of plentiful groundwater.

As more data have become available, it is clear that lateral heterogeneities in the bedrock aquifers significantly impact the amount of stored and recoverable water. Specific yield data obtained from the core hole at Kiowa by the Denver Museum of Nature & Science (Lapey, 2001; Woodard et al., 2002) have caused the State Engineer's Office to decrease their estimate of theoretically recoverable groundwater from approximately 300 million acre ft to approximately 200 million acre ft (Topper et al., 2003, p. 93). As additional data are obtained, this number is likely to decline further because the water yield characteristics of the distal, less-favorable portion of the Basin are presently

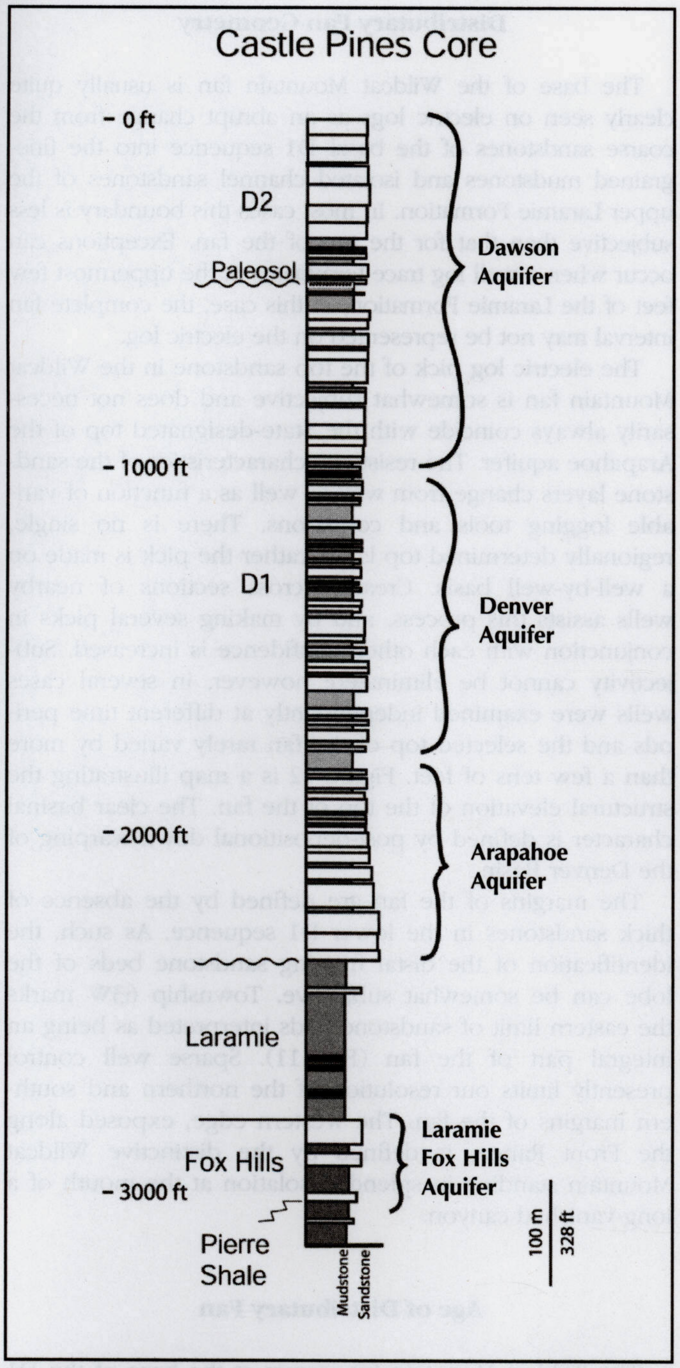

Figure 6. Castle Pines core sketch illustrating the stratigraphic succession representing the aquifers in the Denver Basin. This core was obtained in 1987 by the USGS from a location 6 miles NNW of Castle Rock (Robson and Banta, 1993).

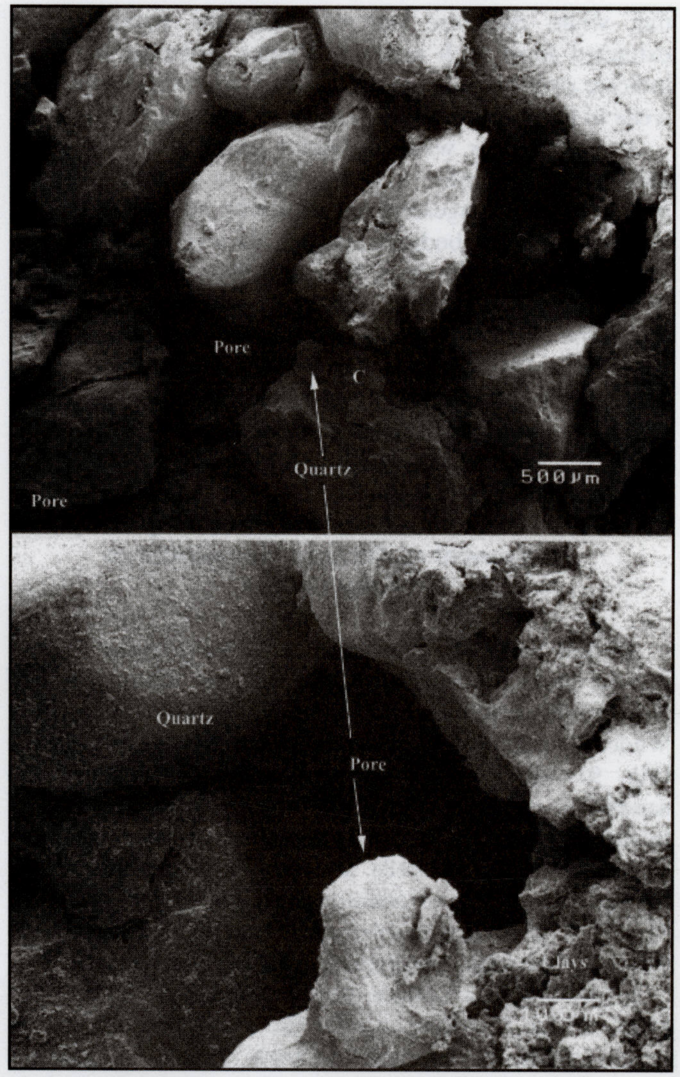

Figure 7. Scanning electron photomicrographs of Arapahoe aquifer sandstone from a depth of 2151.8 feet in the Castle Pines core. Note the large and well-interconnected pore spaces. The scale bar in the upper photo is 0.5 mm and the central part of the upper photo is enlarged below. Photos are courtesy of Lou Taylor.

less-well documented. In any case, taken in isolation, this theoretical water yield is misleading as its recovery would require the drilling of deep, prohibitively expensive, and closely-spaced water wells across the entire Basin, even in areas far-removed from demand.

Robson (1987, p. 22) discusses the falling potentiometric surface in the Arapahoe aquifer, but the data were insufficient to reveal general trends. Crifasi (1992) used electric log patterns to define sandstone/shale ratios and to create isopach maps of the Denver Basin aquifers. His map patterns and interpretations show the aquifers to be derived from mountain sources and his work helped set the stage for this study.

Topper et al. (2003) describe water level declines in the Arapahoe aquifer of up to 30 ft/yr and present a map (their p. 90) illustrating a region between Aurora and Parker where the aquifer experienced greater than 250 ft of decline from 1991 through 2000. They also point out that while data are not compiled for water volume extracted from each separate aquifer, estimates for 1995 indicate over 445,000 acre ft of water was withdrawn from wells in the Denver Basin (Topper et al. 2003, p. 95).

As demand for water resources grows along the Front Range urban corridor, it is important to provide planning and resource management agencies with up-to-date geological models of the bedrock aquifers. As a result of the Denver Museum of Nature & Science's Denver Basin Project (Johnson and Raynolds, 2002; Raynolds and Johnson, 2003), the chronostratigraphy and the stratigraphic architecture of the Denver Basin has become considerably better known; this contribution presents an updated interpretation of the stratigraphic architecture of the Arapahoe aquifer.

Wildcat Mountain distributary fan, the principal component of the Arapahoe aquifer in Douglas County

Wildcat Mountain (Fig. 8) is an isolated massif located on the western margin of the Denver Basin, west of Sedalia (Raynolds and Johnson, 2003). The outcrops at Wildcat Mountain represent amalgamated alluvial channels (Fig. 9) composed of coarse-grained and feldspar-rich sandstone reflecting their derivation from eroding granite in the Front Range. These exposed rocks have been tied directly to selected wells and to the Castle Pines core through a network of cross-sections such as illustrated in Fig. 10. The rock outcroppings of coarse sandstone reinforce the lithologic interpretations of the electric logs.

In the Douglas County area, the water-producing portions of the Arapahoe aquifer are composed of coarse-grained feldspar-rich sandstone beds. Figure 11 illustrates the thickness distribution pattern of the sandstone beds in the Arapahoe aquifer in this area. This contoured map of sandstone aggregate thickness defines a large lobe-shaped feature with an apex in the vicinity of Wildcat Mountain. The subsurface lobe is named the Wildcat Mountain distributary fan after this topographic feature and its fan-like subsurface geometry (Raynolds and Johnson, 2003). The proximal exposures of the fan are fluvial facies, and debris flow textures are extremely rare. The fan is properly considered a fluvial distributary fan, effectively the proximal portion of a river system rather than an alluvial fan (Blair and McPherson, 1994). As shown on Figure 11, there are over 400 ft of net sandstone in the central portion of the fan. As seen on electric logs, these sandstone beds are relatively well-connected and amalgamated, enhancing the aquifer characteristics of the unit. The sandstone beds occur within a gross interval that is up to 600 ft thick. Because this map represents the aggregated sandstone beds in the fan, sub-lobes at varying stratigraphic levels are composited.

Distributary Fan Geometry

The base of the Wildcat Mountain fan is usually quite clearly seen on electric logs as an abrupt change from the coarse sandstones of the basal D1 sequence into the fine-grained mudstones and isolated channel sandstones of the upper Laramie Formation. In most cases this boundary is less subjective than that for the top of the fan. Exceptions can occur when a well log trace terminates in the uppermost few feet of the Laramie Formation; in this case, the complete fan interval may not be represented on the electric log.

The electric log pick of the top sandstone in the Wildcat Mountain fan is somewhat subjective and does not necessarily always coincide with the State-designated top of the Arapahoe aquifer. The resistivity characteristics of the sandstone layers change from well to well as a function of variable logging tools and conditions. There is no single, regionally determined top layer; rather the pick is made on a well-by-well basis. Creating cross sections of nearby wells assists this process, and by making several picks in conjunction with each other, confidence is increased. Subjectivity cannot be eliminated; however, in several cases wells were examined independently at different time periods and the selected top of the fan rarely varied by more than a few tens of feet. Figure 12 is a map illustrating the structural elevation of the top of the fan. The clear basinal character is defined by post-depositional down-warping of the Denver Basin.

The margins of the fan are defined by the absence of thick sandstones in the lower D1 sequence. As such, the identification of the distal fringing sandstone beds of the lobe can be somewhat subjective. Township 63W marks the eastern limit of sandstone beds interpreted as being an integral part of the fan (Fig. 11). Sparse well control presently limits our resolution of the northern and southern margins of the fan. The western edge, exposed along the Front Range, is defined by the distinctive Wildcat Mountain standing in splendid isolation at the mouth of a long-vanished canyon.

Age of Distributary Fan

The Wildcat Mountain fan occurs at the base of the D1 sequence. Estimates of sedimentation rates in this interval are derived from analysis of age-control in the Castle Pines core by Hicks et al. (2003). At a reported average sediment accumulation rate of 137 m/million years, the 183 m (600 ft) of fan material accumulated in about 1.3 Ma, suggesting the age of the fan ranges from 68 Ma (top of Laramie Formation, Hicks et al., 2003) to about 66.7 Ma. Thus, the fan accumulated during the first third of the time represented by the D1 sequence (Raynolds, 2002). The termination of the fan appears to represent a shift in fluvial regime from

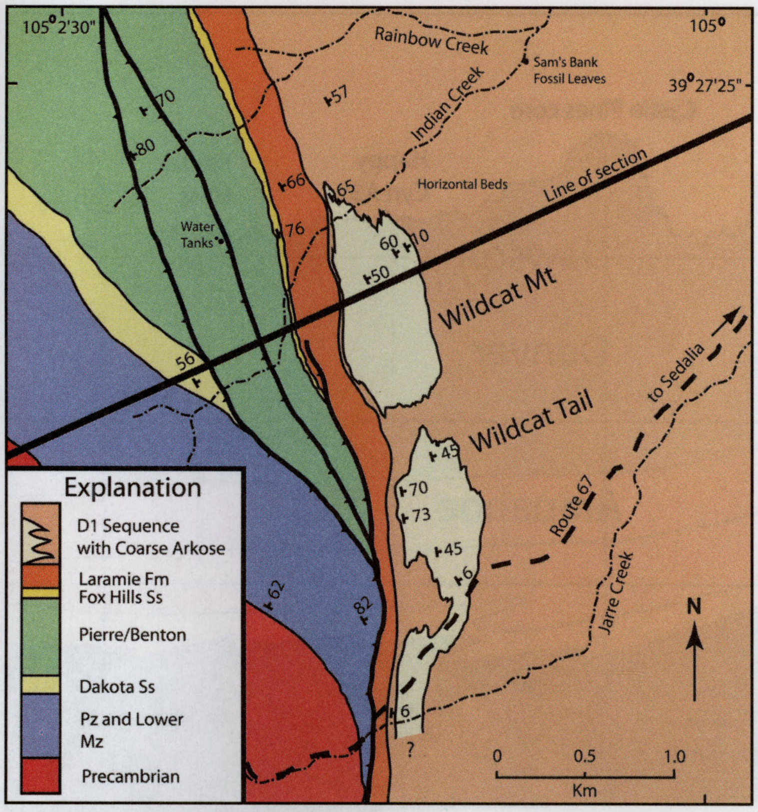

Figure 8. Geologic map of Wildcat Mountain area with the line of section illustrated. See Figure 1 for location. Map modified from Scott (1963) and Kinnaman (1954).

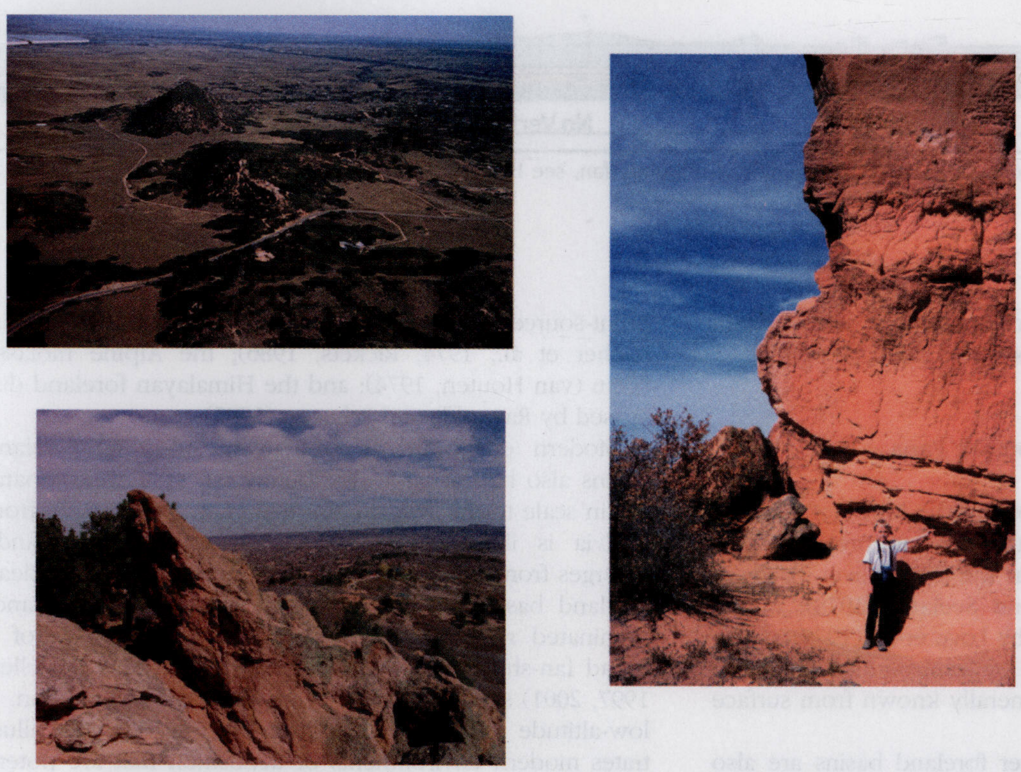

Figure 9. Photographs of outcrops of coarse arkosic sandstone on Wildcat Mountain. Upper left is aerial view looking to the north, route 67 is in the foreground. The resistant arkosic channel deposits make up this isolated ridge.

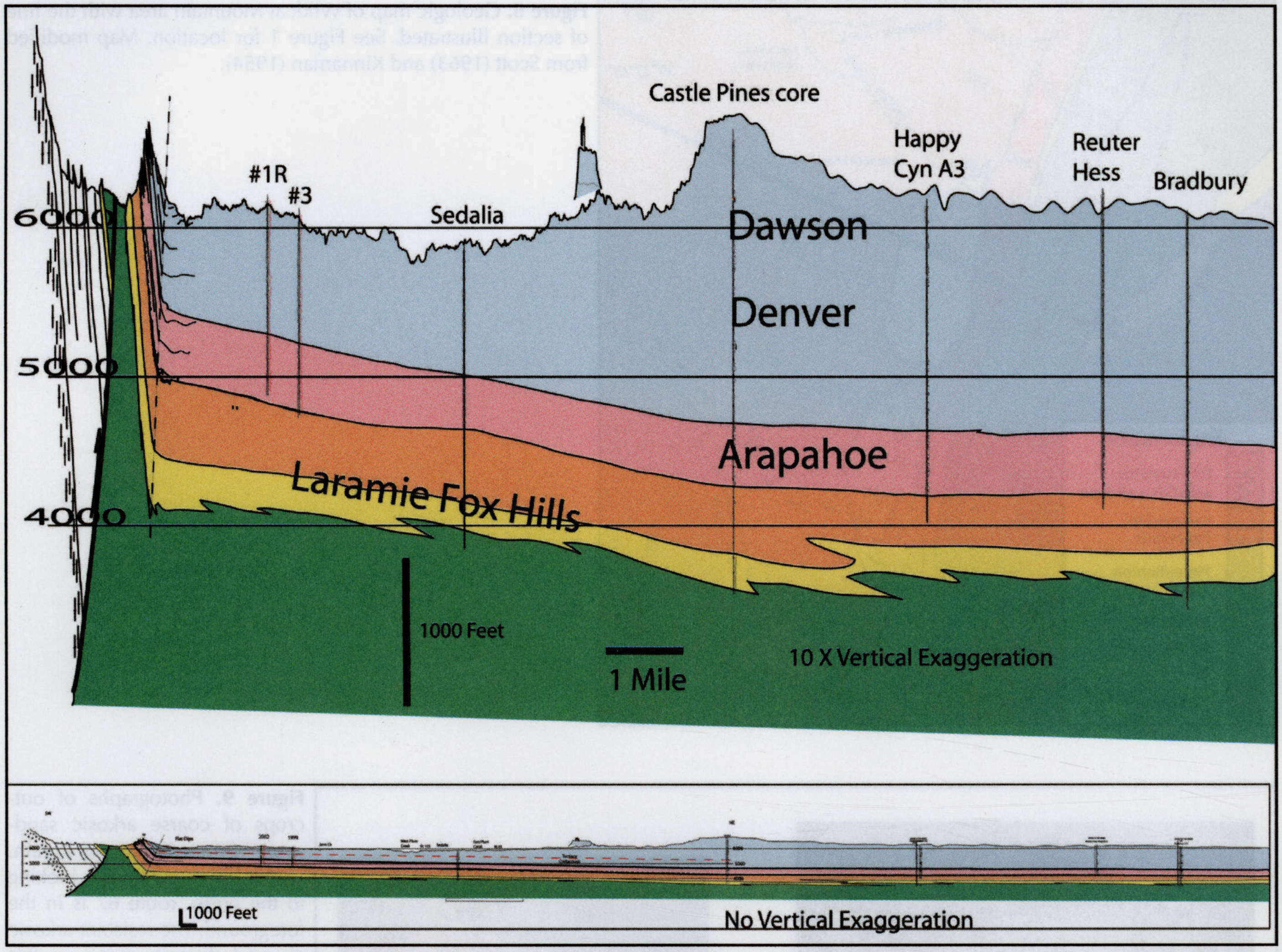

Figure 10. Dip oriented cross section of the Wildcat Mountain distributary fan, see Figures 1 and 8 for location. The section is shown at 10X vertical exaggeration (top) and at true-scale (bottom).

controlled and localized debouchement from the mountain front to a considerably less constrained drainage system.

Analog Distributary Fans

Other Laramide basins have coarse lobes of synorogenic strata on their margins that are interpreted as fossilized distributary fans, e.g., in the Wind River Basin as discussed by Soister (1968) and Seeland (1978); in the Green River Basin as reported by Love et al. (1978) and in the Big Horn Basin as reported by Johnson and Middleton (1990). These examples are generally known from surface outcrops.

On a world-wide basis, other foreland basins are also known to have had long-lived river systems that contributed point-sourced clastics -for example the Alberta Basin (Eisbacher et al., 1974; Rickets, 1986); the Alpine molasse basin (van Houten, 1974); and the Himalayan foreland discussed by Raynolds and Johnson (1985).

Modern environments in actively subsiding foreland basins also harbor large distributary fan systems comparable in scale to the Wildcat Mountain fan. An example from Bolivia is illustrated (Fig. 13) where the Rio Grande emerges from the Andes and flows east across the Andean foreland basin. The lateral migration of this large sand-dominated river has resulted in the accumulation of a broad fan-shaped distributary lobe (Horton and DeCelles, 1997, 2001) similar in scale to the Wildcat Mountain fan. A low-altitude air photograph from Bolivia (Fig. 14) illustrates modern environments of deposition that are potential analogs for ancient systems in the Denver Basin.

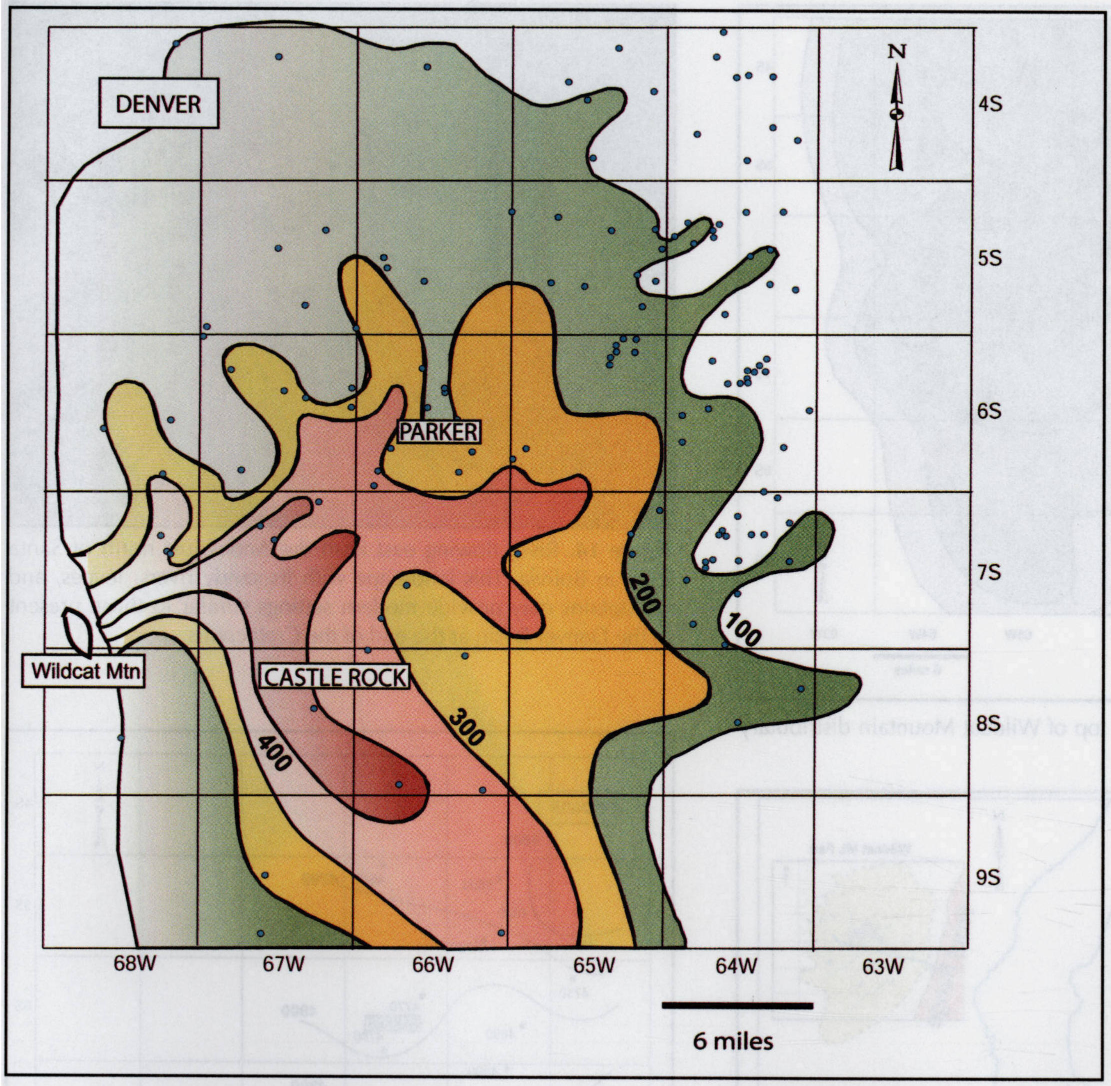

Figure 11. Net sandstone isopach map of the Wildcat Mountain distributary fan, units are in feet. Note that the map is schematic on the northern and southern portions of the fan due to sparse data. The interpreted electronic logs are archived at the Denver Museum of Nature & Science.

Current Water Levels in the Arapahoe Aquifer: The potentiometric surface in 2004

The State Engineer's Office publishes annual tables documenting water levels in monitoring wells in the Denver Basin (State Engineer's Office, 2003). Figure 15 is a map showing the 2004 potentiometric surface elevation in the Arapahoe aquifer (effectively coincident with the Wildcat Mountain fan) derived from data for 14 wells published by the State Engineer's Office and one well from the Thunderbird water district. Figure 16 shows the spatial distribution of the potentiometric surface information and establishes the regional nature of the declining water levels. Figure 17 illustrates the elevation difference between the top of the Arapahoe Lobe and the potentiometric surface and Figure 18 shows the estimated year at which the Arapahoe aquifer will start the transition from confined to unconfined conditions if rates of decline continue at the presently observed values of approximately one inch per day, or 30 ft/yr.

DENVER AND DAWSON AQUIFERS

As the conditions for fan formation became less favorable, the paths followed by river systems depositing sandstone in the Denver Basin became less organized and less predictable. Their courses played back and forth across the Basin area, likely draining to the north-northeast. It is rare, even in cases of closely-spaced wells, to be able to confidently identify the same channel sandstone in any two wells in the Dawson and the Denver aquifers. While sandstone beds are more concentrated closer to the mountain front (Crifasi, 1992), few local sandstone distribution patterns

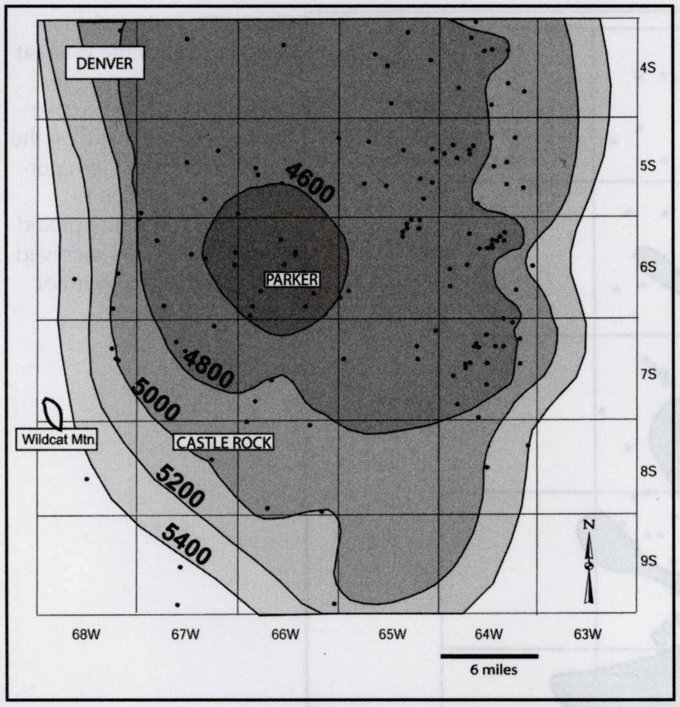

Figure 12. Structure map on top of Wildcat Mountain distributary fan.

Figure 14. River flowing east from the Andes just north of Santa Cruz in Bolivia. This landscape with its sandy rivers, levees, and floodplains may provide modern settings similar to those present in the Denver Basin at the end of the Cretaceous.

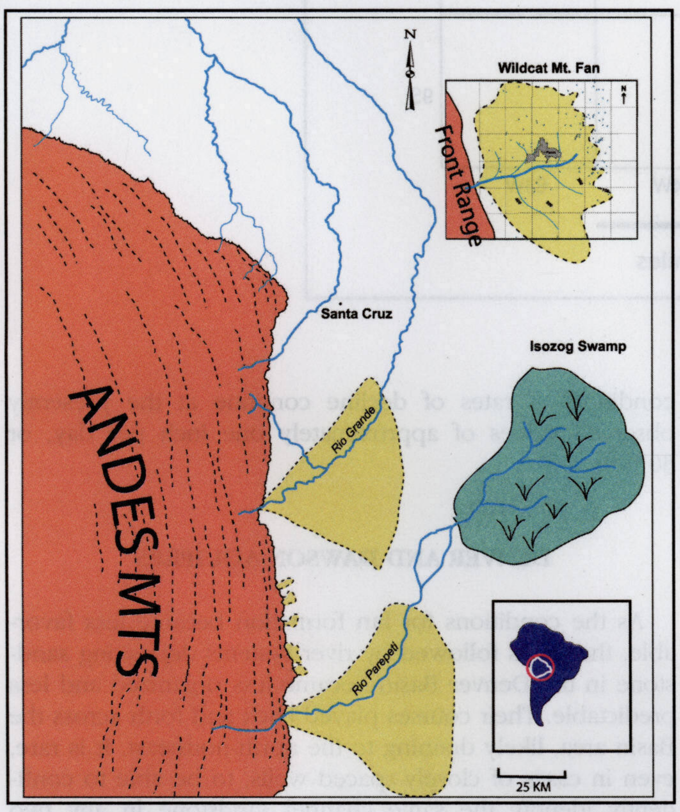

Figure 13. Map of eastern Bolivia showing large fan systems debouching from the Andes. The inset figure is the Wildcat Mountain distributary fan at the same scale.

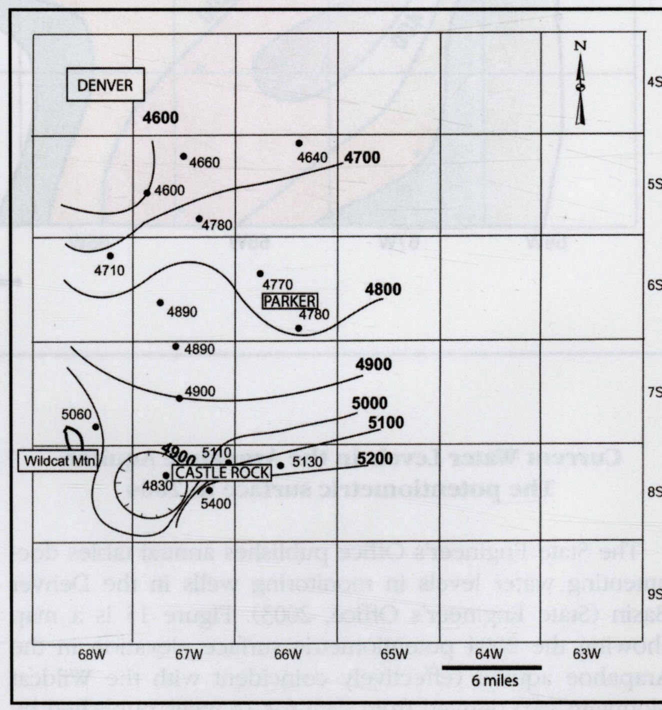

Figure 15. 2004 potentiometric surface map of the Arapahoe aquifer in the Douglas County area derived from curves in figure 16 and a well from the Thunderbird water district. Elevations in feet.

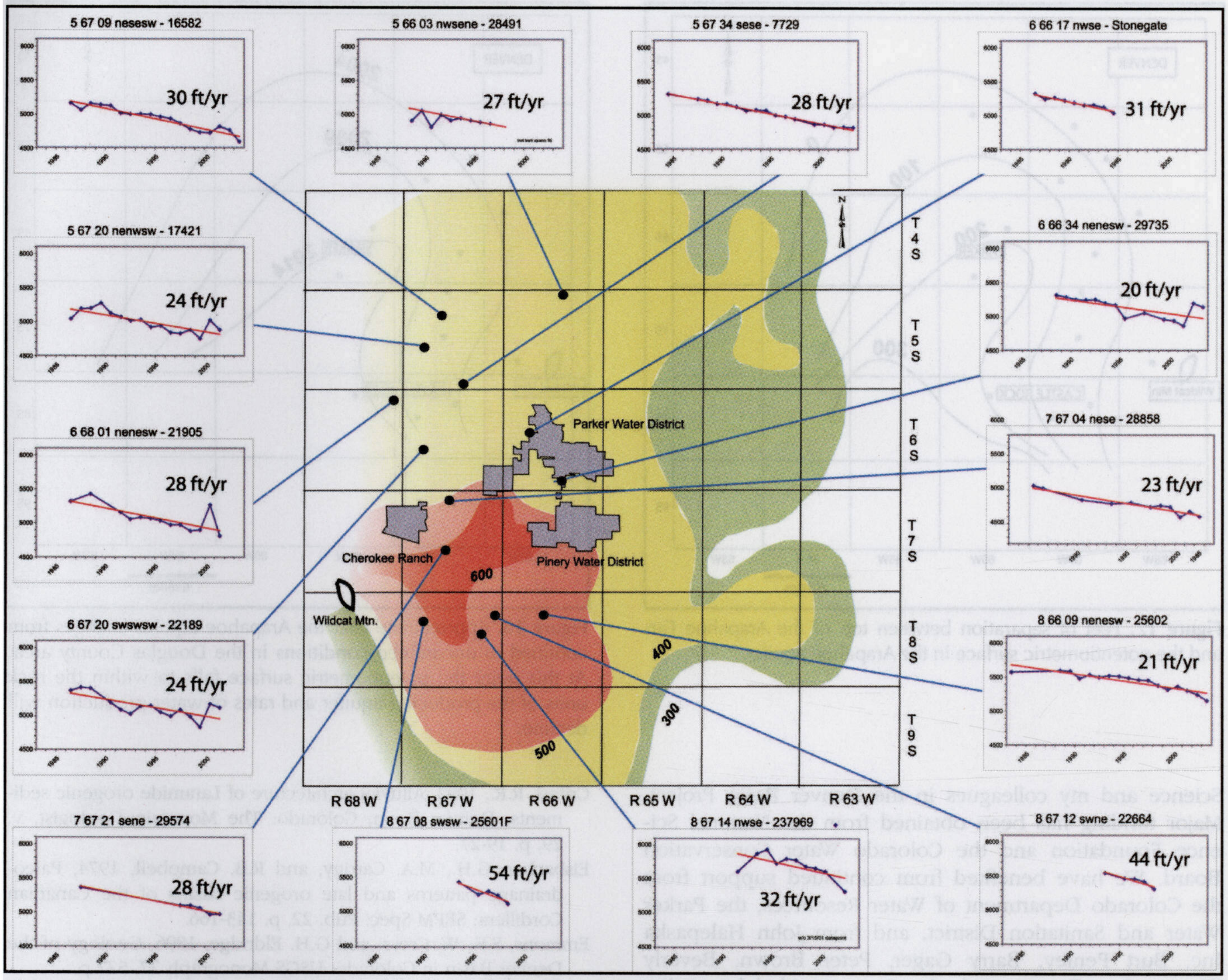

Figure 16. Composite map of the Arapahoe aquifer with decline curves from 14 wells in the Douglas County area. Data from the Colorado State Engineer's Office.

are observable, as sandstone beds are isolated and generally poorly interconnected in the upper Arapahoe, the Dawson and the Denver aquifers. These aquifer units are made up of a mosaic of lenses and elongated belts of sandstone.

CONCLUSIONS AND RECOMMENDATIONS

Stratigraphic information can aid in developing a better understanding of the three-dimensional character of bedrock aquifers in the Denver Basin. In the current circumstances of intensive well drilling and the resultant depletion of our finite water resources, it is imperative that adequate, reliable, and widespread data be gathered. Additional water-level monitoring wells need to be constructed. Fluid flow models need to be run using databases that incorporate stratigraphic models derived from studies such as this. Declining water levels and associated diminished water-yields from the Arapahoe aquifer in the Douglas County area will cause communities to seek alternate potable water supplies.

ACKNOWLEDGMENTS

I would like to acknowledge the ongoing support of a large group of people at the Denver Museum of Nature &

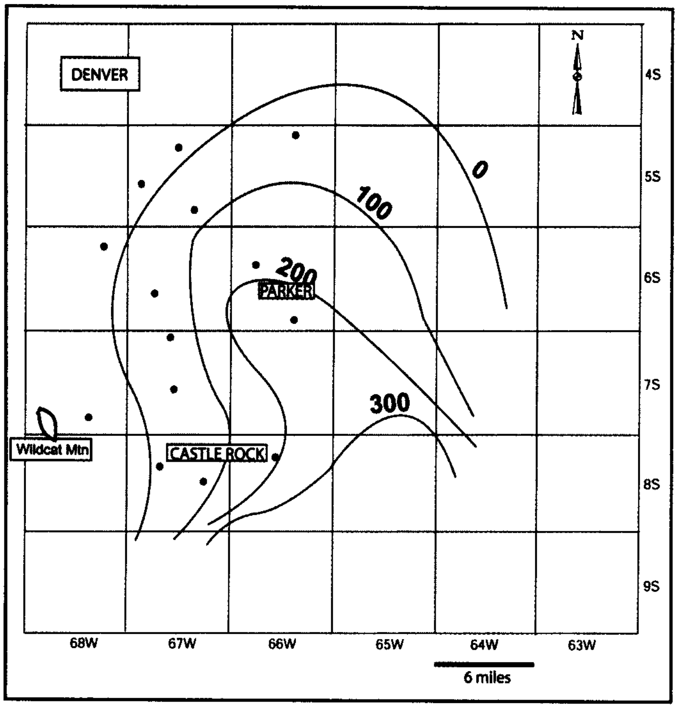

Figure 17. Feet of separation between top of the Arapahoe Fan and the potentiometric surface in the Arapahoe aquifer.

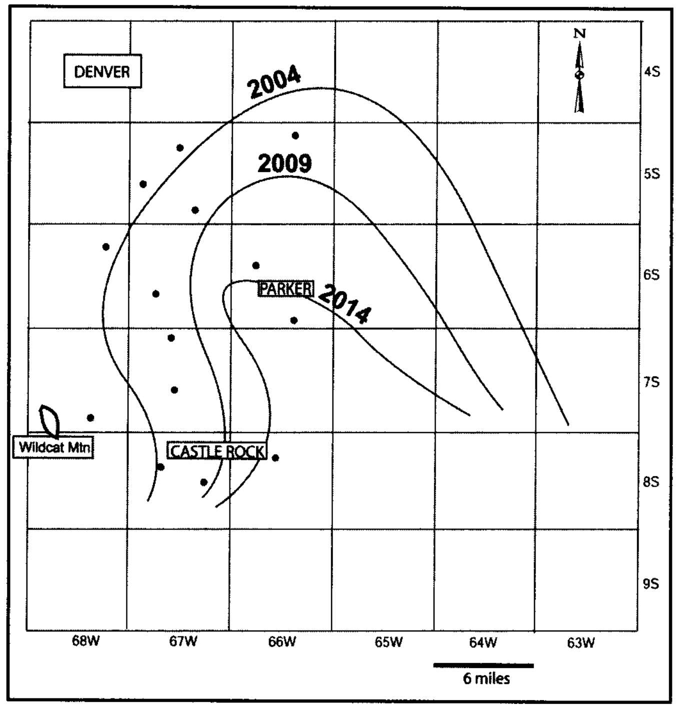

Figure 18. Approximate year the Arapahoe aquifer changes from confined to unconfined conditions in the Douglas County area. At this point the potentiometric surface falls to within the rock units of the producing aquifer and rates of water production will decline.

Science and my colleagues in the Denver Basin Project. Major funding has been obtained from the National Science Foundation and the Colorado Water Conservation Board. We have benefited from continued support from the Colorado Department of Water Resources, the Parker Water and Sanitation District, and from John Halepaska Inc. Burt Penley, Barry Gager, Peter Brown, Beverly Weaver, Sam Brown, and Alex Port provided hospitality and helpful information in the Rainbow Creek area. Tim Killeen was most helpful in Bolivia. Figure 5 was drafted by Jeff Corbin. Kirk Johnson, Susan Landon, Mary Raynolds, Michele Reynolds and Beth Ellis provided helpful comments on drafts of this paper. John Halepaska, John Moore, and Kyle Murray provided hydrologic advice and perspective, and their assistance is gratefully recognized.

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